On the Formation of Brown Dwarfs

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ABSTRACT

The observational properties of brown dwarfs pose challenges to the theory of star formation. Because their mass is much smaller than the typical Jeans mass of interstellar clouds, brown dwarfs are most likely formed through secondary fragmentation processes, rather than through the direct collapse of a molecular cloud core. In order to prevent substantial post-formation mass accretion, young brown dwarfs must leave the high density formation regions in which they form. We propose here that brown dwarfs are formed in the circumbinary disks. Through post-formation dynamical interaction with their host binary stars, young brown dwarfs are either scattered to large distance or removed, with modest speed, from their cradles.

Subject headings: star formation – brown dwarfs – binary stars

1. Introduction

Brown dwarfs are entities with mass below that require for hydrogen burning to ignite ($< 0.075 M_{\odot}$) and above that associated with gaseous giant planets ($\sim$ 13 Jupiter masses). Although the existence of brown dwarfs was proposed by Kumar in 1963, their cool dim nature consigned them to a strictly theoretical status for more than three decades. Recently, however, improved observational capabilities have led to the discovery of many brown dwarfs, prompting a renaissance in our understanding of these objects. Brown dwarfs are now known as companions to main sequence stars (Nakajima et al. 1995), as cluster members (Rebolo et al. 1995, Lucas & Roche 2000) as field objects (Ruiz et al. 1997), and as binary pairs (Basri & Martin 1999). Surveys such as the Deep Near-Infrared Survey (DENIS) (Epchtein et al. 1994), and the 2 Micron All-Sky Survey (2MASS) (Skrutskie et al. 1997), are uncovering brown dwarfs in statistically significant quantities.

A number of planet search programs based on the radial velocity method have failed to uncover brown dwarfs orbiting in close proximity (with separation less than $\sim$ 1 AU) to stellar mass primaries (Marcy & Benitz 1989; Cochran & Hatzes 1994; Mayor & Queloz 1995; Walker et al. 1995). Brown dwarfs also appear to be rare at intermediate separations ($1 < r <\sim$ a few AU) as evidenced by the speckle imaging survey carried out by Henry & McCarthy (1993). Similarly, Oppenheimer et al. (2001) did a survey for companions of stars within 8 pc of the Sun and found only one brown dwarf. A small number of brown dwarfs have, however been found as binary companions lying at separations much greater than a few AU (Neuhäeuser et al. 2000). Gizis et al. (2001) derived the wide companion frequency and said the current data indicated that about one percent of $M_{\rm V} < 9.5$ primaries have wide L dwarf companions; the brown dwarf fraction should be 5-13 times higher. To further complicate matters, brown-dwarf binary pairs (i.e. both components of the binary are brown dwarfs) have been discovered. Basri & Martin (1999) claimed that they detected

the first spectroscopic brown-dwarf pair with a period of about 5.8 days only. Koerner et al. (1999) found three brown-dwarf pairs with the projected physical separations between 5 and 10 AU. Recently, Gizis et al. (2003) presented analysis of HST images of 82 nearby field late M and L dwarfs and estimated that binary fraction is about 10 to 20 percent in the range 1.6–16 AU.

Because the mass of brown dwarfs is much smaller than the usual Jeans mass for a typical molecular cloud, Lin et al. (1998) claimed that the encounter between two protostellar discs might increase the Jeans mass locally. Reipurth & Clarke (2001) suggested that brown dwarfs are substellar objects because they have been ejected from newborn multiple systems. They use a simple model of timescales to show that this could happen. Bate et al. (2002) used a smoothed particle hydrodynamics code to show that brown dwarfs could be formed through the collapse and fragmentation of a turbulent molecular cloud multiply and thus confirmed what was suggested by Reipurth & Clarke (2001).

In this paper, we propose a formation scenario for brown dwarfs which provides a natural explanation for the current observational situation. Numerical simulations have confirmed that a rotating protostellar cloud may induce hierarchical fragmentation and the emergence of very low mass objects (Burkert & Bodenheimer 1996). However, these entities continue to grow as they merge with each other and accrete from the residual infalling envelope of the cloud unless they are ejected from the dense central regions (Bate et al. 2002). In many cases, the low-mass objects become the binary companions of a dominant massive protostellar object. In such a binary configuration, gas in the residual rotating infalling envelope settles onto a circumbinary disk and is then preferentially accreted by the less massive member through the outer Lagrangian point. This tendency generally leads the binaries to gradually acquire comparable masses. Subsequently, mass accumulation in circumbinary disk may lead to the collapse of low mass entities and become candidates of

brown dwarfs.

Therefore, it seems natural to suggest that perhaps many brown dwarfs could be formed through fragmentation of the circumbinary disks. We study the "escape zone" where the brown dwarfs could be ejected and become field stars. We demonstrate that in some cases, the brown dwarfs get ejected but in other cases, they could become long-period companion. We also study the criteria that the brown-dwarf pair can survive. However, we do not intend to study the problem of brown dwarf desert here (please see the model by Armitage & Bonnell 2002). In Section 2, we present the results for single brown dwarf. The study about formation of brown-dwarf pairs would be in Section 3. We provide concluding remarks in Section 4.

2. Stability of brown dwarf companion around binary stars

We now investigate the orbital stability and evolution of brown dwarfs formed in circumbinary rings. These companions are perturbed by the tidal disturbance of the binary star's gravitational potential. For computational convenience, we assume these newly fragmented brown dwarfs quickly become centrally condensed and the residual gas does not contribute significantly to the gravitational potential such that the dynamics of the system may be described by a few-body approximation. A direct force integration of the equation of motion is required for the computation of the orbital evolution of this system. We adopt a numerical scheme with Hermite block-step integration which has been developed by Sverre Aarseth (Markino & Aarseth 1992, Aarseth, Lin & Palmer 1993).

In this section, we further simplify the interaction procedure to a three-body (the host binary star plus a brown dwarf) problem. The mass of each brown-dwarf fragment is sufficiently small that they do not significantly perturb each other on the short term of

several thousand binary periods. In order to make a direct comparison with some existing results, we first treat the brown dwarfs as massless particles. But, in general, we carry out full 3-body integration in which contribution due to the finite mass of the brown dwarf is included.

We consider a range of ratio ($\mu = M_1/(M_1 + M_2)$) of masses (M_1 and M_2) for the two components of the binary stars. Following the approach by Holman & Wiegert (1999), we consider, for the host binary system, a range of orbital eccentricity (e_*). The semi major axis of the binary is set to be unity such that all other length scales are scaled with its physical value. We also adopt $G(M_1 + M_2) = 1$ such that the binary orbital period is 2π. In this paper, the total mass of the central binary is assumed to be 1 $M_\odot$ in real unit.

Since we assume they are formed in circumbinary rings, we consider brown dwarfs with orbital semi major axis larger than that of the binary system. At the onset of the computation, all three stars are located at their apocenter with respect to their common center of mass. It is possible that the fragments may have a range of orbital eccentricity (e_b). Here, we consider two limiting eccentricity for the brown dwarf ($e_b = 0$ and 0.4). We also set the ratio (μ_b) of brown dwarf's mass to that of the binary to be 0.05 and we assume brown dwarfs rotate in the same direction as the orbit of the binary secondary.

2.1. Ejection criteria

We choose a range of initial orbital semi major axis for the brown dwarf for the $e_b = 0$ case. For each set of model parameters, we adopt four values for the brown dwarf's angle of apocenter, 0°, 90°, 180° and 270° with respect to that of the binary system.

We are primarily seeking a critical initial semi major axis (a_c), larger than which the brown dwarf survives the binary system's perturbation within a timescale T_d. Our definition

of survival is that the distance from the center of mass of the system to the brown dwarf (starting with all four values of the apocentric arguments) must smaller than a critical value R_d. R_d can be chosen to be a number which is much larger than the binary separation, say 10 or 100 times binary separation. The choice of this number would not affect the results much. Because as long as it is ejected, it will go through both the boundary of 10 and 100 binary separation within T_d. If it is stable, it will stay within 10 binary separation always. Only marginally stable cases are more complicated, but these marginal cases only happen when initial semi major axes are around particular values. Thus, we set the value of R_d to be 25 binary separations. In order to compare with the results of Holman & Wiegert (1999), we choose $T_d = 10^4$ binary period, i.e. $T_d = 2\pi \times 10^4$. Based on several test runs, we find that the value of a_c does not change significantly if T_d is increased to 10^6 binary period. Thus, we find a_c to be a useful parameter to classify our results. Although we use a totally different numerical scheme as Holman & Wiegert (1999), we are able to precisely reproduce the results in Table 7 of their paper when we set the mass of brown dwarf to be zero as they have. But in general, we choose $\mu_b = 0.05$.

From these models, we find that the brown dwarf's "escape zone" (with semi major axis $a < a_c$) is expanded slightly when they have finite mass (see Fig.1 & 2 for the comparison.) The expansion of the "escape zone" is larger for $\mu = 0.1$ cases than that for the $\mu = 0.5$ cases because the motion of secondary star is more affected by the finite mass of the brown dwarf. This effect is particularly noticeable for the $\mu = 0.1$ and $e_* = 0.6$ case where a_c is expanded from 3.9 of massless particles to 6.0 of brown-dwarfs with $\mu_b = 0.05$. The hydrodynamical simulations indicate that fragmentation of circumbinary disks occurs primarily at around a few binary separation away from their center of mass because this is the location where disk gas may accumulate as a consequence of binary star's tidal torque. Observations by Beckwith et al. (1990) indicated that about 42 percent of young stars have discs. These discs' survival times are from 10^6 to 10^7 years and masses range from

10^{-3} to 1 $M_{\odot}$. For example, Roddier et al. (1996) showed that the GG Tauri system has a circumbinary ring with the density peak at radius about 2.7 times the semi major axis of the central binary orbit. The average density of this circumbinary ring is only about 0.1 to 0.2 of the peak value from 60 AU to 160 AU, then increases rather sharply with a constant slope to reach the peak at 250 AU and finally, decays roughly as a power law, R^{-2}, until 460 AU from the center (see Fig. 9 of their paper). Thus, *most of the low-mass fragments formed in the circumbinary rings have a high probability of being ejected by the gravitational perturbation of their host binary systems.*

In general, the fragments might not move on circular orbits. It would be interesting to consider the models in which the brown dwarfs are assumed to move on eccentric orbits initially. Since the circumbinary ring of GG Tauri is actually an ellipse with the eccentricity about 0.2 (Roddier et al. 1996) and the fragments formed there might not exactly move along this ellipse, these fragments' initial orbital eccentricities could be even larger.

Therefore, we now consider a series of models with $e_b = 0.4$ while all other parameters are similar to those for the $e_b = 0$ case. The increases in a_c in Fig. 1 and Fig. 2 clearly indicate that brown dwarfs with eccentric orbits are definitely less stable than those with circular orbits.

2.2. Large radial excursion of marginally stable systems.

In general, the binary systems and the fragments formed in unstable circumbinary rings have non circular orbits. Thus, most brown dwarfs formed close to the binary are likely to be ejected. But, brown dwarfs' with initial semi major axis $a_b \sim a_c$, can be scattered to large distances from the center of mass of the system without escaping from its gravitational potential within the timescale T_d (although it might still escape after all). We

call these cases “marginally stable” because they could be unstable if one could integrate for larger timescale or use non-numerical methods to prove the instability rigorously.

In Fig. 3, We illustrate three such examples each with $a_b \sim a_c$. In model 1, we choose $\mu = 0.1$, $e_* = 0.4$, $a_b = 4.4$, $e_b = 0$ and the argument of brown dwarf's apogee, $\theta_b = 90^o$. In this case, the brown dwarf reaches to 200 binary separation by the end of simulation, i.e. $t = T_d$. In model 2, ($\mu = 0.1$, $e_* = 0.6$, $a_b = 7.8$, $e_b = 0.4$, and $\theta_b = 180^o$), the brown dwarf's orbit expands to 50 times binary's initial separation at $t \sim 0.6T_d$. But, subsequently at $t = T_d$, the extent of the brown dwarf's radial excursion is reduced to approximately its initial value. In model 3, ($\mu = 0.5$, $e_* = 0.2$, $a_b = 6.3$, $e_b = 0.4$, and $\theta_b = 270^o$), the excursion reaches to 100 initial binary separation. These examples indicate that the existence of wide and marginally stable orbits and that *under some marginal circumstances, brown dwarfs can be scattered to large distance from but remain bound to some main-sequence binary stars for a particular time scale.* The discovery of a brown dwarf candidate at a distance of $\sim$ 100 AU from a young binary star, TWA 5 may be examples of such a system (Lowrance et al. 1999).

2.3. Ejection speed of escapers

Brown dwarfs with $a_b < a_c$ are ejected from the gravitational potential of their host binary system. We now examine their escape speed. For this study, we first consider the case with $\mu = 0.5$ and $e_* = 0$. We approximate the brown dwarf companions as massless particles with $e_b = 0$ initially. Because brown dwarfs are assumed to be test particles and thus they do not interact each other, we can put more particles in one simulation to investigate different initial conditions and get better statistics. We place 24 particles around a ring with a radius $a = 1.3$ from the center of mass of the binary. These particles are initially separated in the azimuthal direction by 15^o between any two closest pairs. An

additional 24 particles with similar azimuthal spacing are placed on a circle with $a = 1.5$. All of these particles have $a < a_c$ such that all of them are ejected from the proximity of the binary's orbit within 10^4 binary periods.

We also carried another series of calculations with $\mu = 0.5$ and $e_* = 0.2$ where 24 particles are placed on each of two concentric rings with $a = 1.9$ and 2 respectively. Their azimuthal positions are equally separated by 15^o. Finally, for the $e_* = 0.4$ and 0.6 case, we placed 24 particles in a similar manner on each of two concentric rings with $a = 2.4$ and 2.5. Thus, for each binary star, we place 48 particles with $a < a_c$ around the binary. All of these particles are ejected from the system.

We summarize all the results in Fig. 4 in which we plot the distribution of the escape speed. These results show that the ejection speed is typically half the orbital speed of the binary. For $R_b \sim 3 \times 10^{15}$ cm, $a \sim R_b$, and the total mass of binary system to be $\sim 1 M_\odot$, the binary's orbital speed would need to be $\sim 3 - 5$ km s^{-1}. Our results show that the escaping speed of the brown dwarf ejecta is $\sim 1 - 3$ km s^{-1}. In a young stellar cluster, such as the Orion, this ejection speed is a fraction of the velocity dispersion of the cluster which is in a dynamical equilibrium. Thus, *brown dwarfs ejected from the close proximity of the binary would not generally escape the gravitational potential of the cluster.* This result is consistent with the large concentration of brown dwarfs in young stellar clusters such as the Orion complex (Lucas & Roche 2000).

3. Formation of brown dwarf pairs

Indeed, close brown dwarf binaries have been found (Koerner et al. 1999), but these systems are generally not orbiting around some other binary main sequence stars. Similar to single brown dwarfs, close binary brown dwarfs may also be strongly perturbed by the

gravity of the binary and be ejected.

3.1. Survival of pairs

In order to test the survival probability of the brown dwarf binaries, we first place a massless test particle to simulate the dynamics of a secondary companion around the brown dwarf (For some interesting cases, a series of models with masses for both brown dwarf companions are included). This approximation allows us to first explore the range of parameters which may be favorable for the survival of the brown dwarf pairs. Based on the results in Fig.1 and Fig. 2, we can identify the range of model parameters which leads to ejection of brown dwarf fragments. As a test, we adopt $\mu = 0.5$ for the binary star and choose $\mu_b = 0.05$, $a_b = 2.3$ and apogee at $0°$ for the primary of the brown dwarf binary. The secondary of the brown dwarf binary is assigned with an initial semi major axis 2.5 and apogee at $0°$, thus the separation of the brown-dwarf pair is 0.2 which is inside the Roche radius of the primary ($R_R = (\mu_b/3)^{1/3} = 0.25$). We also assume that the center of mass of the brown-dwarf pair is initially on a circular orbit around the center of mass of the binary system and the brown-dwarf secondary is on a circular orbit around the brown-dwarf primary.

Then, we try four cases of different eccentricities of central binary stars relative to each other: $e_* = 0.0, 0.2, 0.4, 0.6$. Our results indicate that the brown-dwarf pairs would survive their ejection from the neighborhood of the binary in the low-eccentricity ($e_* = 0.0$ and $e_* = 0.2$) limit. But, in the limit that the binary system has a large eccentricity (i.e. for the $e_* = 0.4$ and $e_* = 0.6$ models), the brown dwarf pairs have a tendency to become dissociated. Therefore, it is plausible that brown dwarf pairs may remain bound to each other during their ejection from the binary system's gravitational potential. But, it is also possible for their ejection to produce two freely floating single brown dwarfs.

The above approximation provides a useful tool for us to identify the range of parameters which allows a brown dwarf pairs to survive. The massless approximation for the secondary is applicable to brown dwarf binary with extreme mass ratios. We now takes the next iteration by replacing the ($\mu_b = 0.05$) primary and a massless secondary brown-dwarf pair with a system of two equal-mass ($\mu_b = 0.025$) brown dwarf companions. We find, with identical four sets of model parameters as above, brown dwarf binaries all remain intact as they are ejected by their host binary stars for these four cases $e_* =$0.0, 0.2, 0.4 and 0.6.

We also enlarge the separation of the brown-dwarf binary to 0.3 which is larger than its Roche radius. Again all four sets of initial conditions are used. In all these four cases, the brown dwarf binary is always disrupted during its close encounters with the binary star.

3.2. Pair capture

We now explore the possibility that both brown dwarfs were formed as single brown dwarfs and that they may have captured each other to become a binary. In order to evaluate this probability, we repeat the earlier simulation in which 24 particles are placed in a ring around the binary system (see Section 2.3). The main difference with the earlier models is that a mass of $\mu_b = 0.05$ is assigned to each particles. The corresponding Roche radius for each individual particle is ~ 0.25 which is comparable to their initial separation. All the particles are ejected from the gravitational potential of the binary system but no particle captured any other particle. We thus conclude this second scenario is very unlikely.

4. Concluding Remarks

We have proposed that large number of brown dwarfs are probably formed through fragmentation in circumbinary disks. We study the criteria for ejection from their cradles, the possibility to do large radial excursion for marginally stable systems and also the ejection speed of escapers. In addition to that, we also study the formation of brown-dwarf pairs.

For single brown dwarf satellites around binary systems, our dynamical calculations show that when they are formed in dynamically unstable regions, they are likely to be ejected from the gravitational potential of the binary system. These results provide an explanation for the discovery of field brown dwarfs (Ruiz et al. 1997, Tinney 1998) and also consistent with the discovery of brown dwarfs as cluster members (Rebolo et al. 1995, Lucas & Roche 2000).

For binary brown dwarf satellite pairs, the calculations of four body (main sequence binary with brown-dwarf pair) interaction show that these brown-dwarf pairs can remain to be bound to each other during the ejection if their initial separation is well within their Roche radius (which is typically $R_R \sim 0.2 - 0.25$ binary separation). Thus, *brown dwarf pairs with separations less than their Roche radius are likely to survive the ejection from their host binary star* because the ejection of the brown dwarf does not involve close encounter with either of their two stellar components. In contrast, when their separation is larger than the Roche radius of the brown dwarf pair, the binding force between brown dwarfs is weaker than the tidal force from the central binary so that the brown dwarf pairs are easily disrupted. These results might help to investigate the formation histories of brown-dwarf pairs detected in Koerner (1999) and Basri & Martin (1999).

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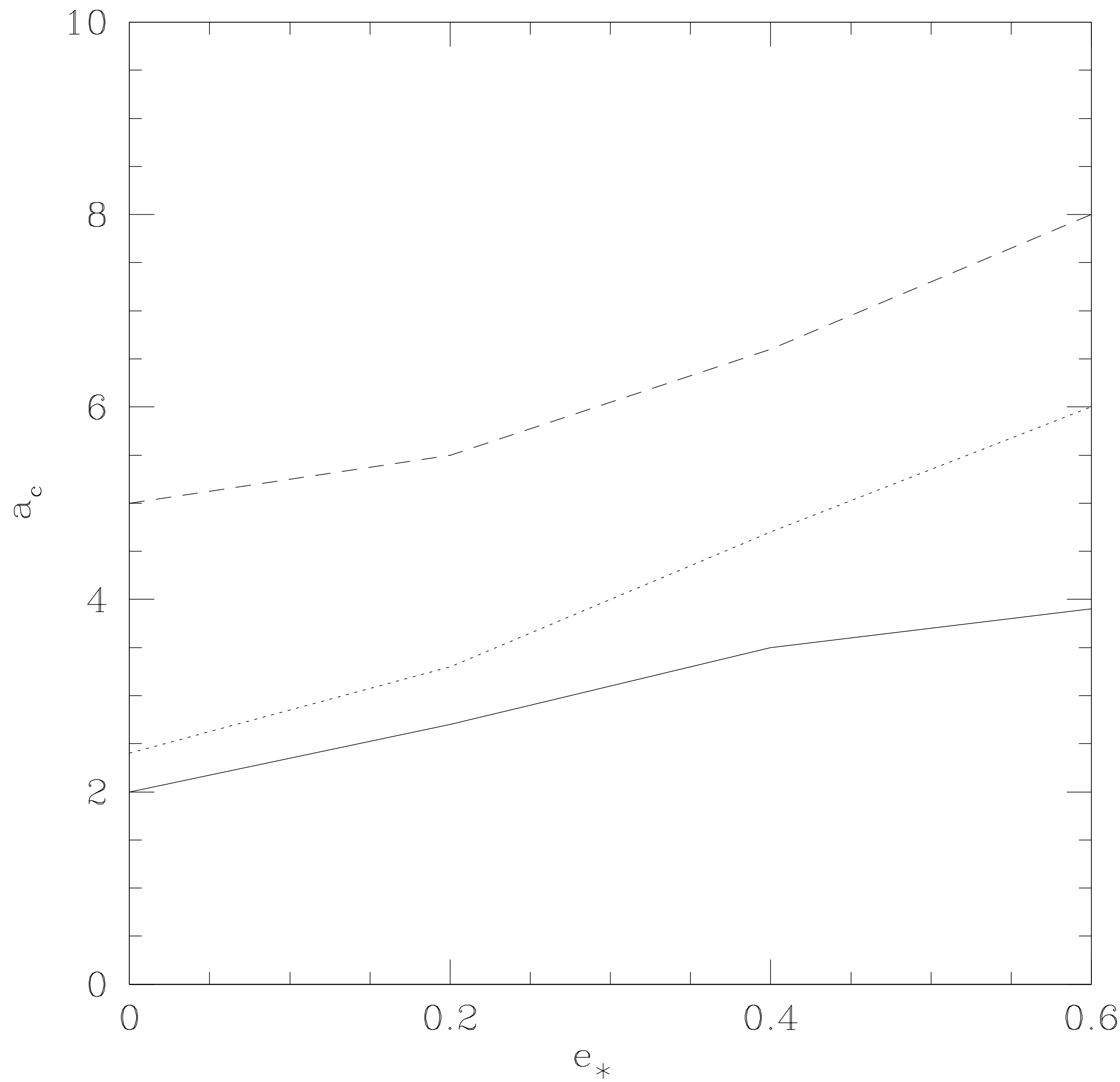

Fig. 1.— The critical semi major axis as function of eccentricity when the mass ratio of the binary system $\mu = 0.1$. The simulations were run at $e_* = 0.0$, 0.2, 0.4 and 0.6 and then the results connected by lines. The solid line represents the result for models with brown dwarfs been treated as massless test particles which initially move on circular orbits. The dotted line represents the results for models in which brown dwarfs are assigned with finite mass $\mu_b = 0.05$ and assumed to have circular orbits initially. The dash line represents the results of models in which brown dwarfs have mass $\mu_b = 0.05$ and have initial eccentricity $e_b = 0.4$.

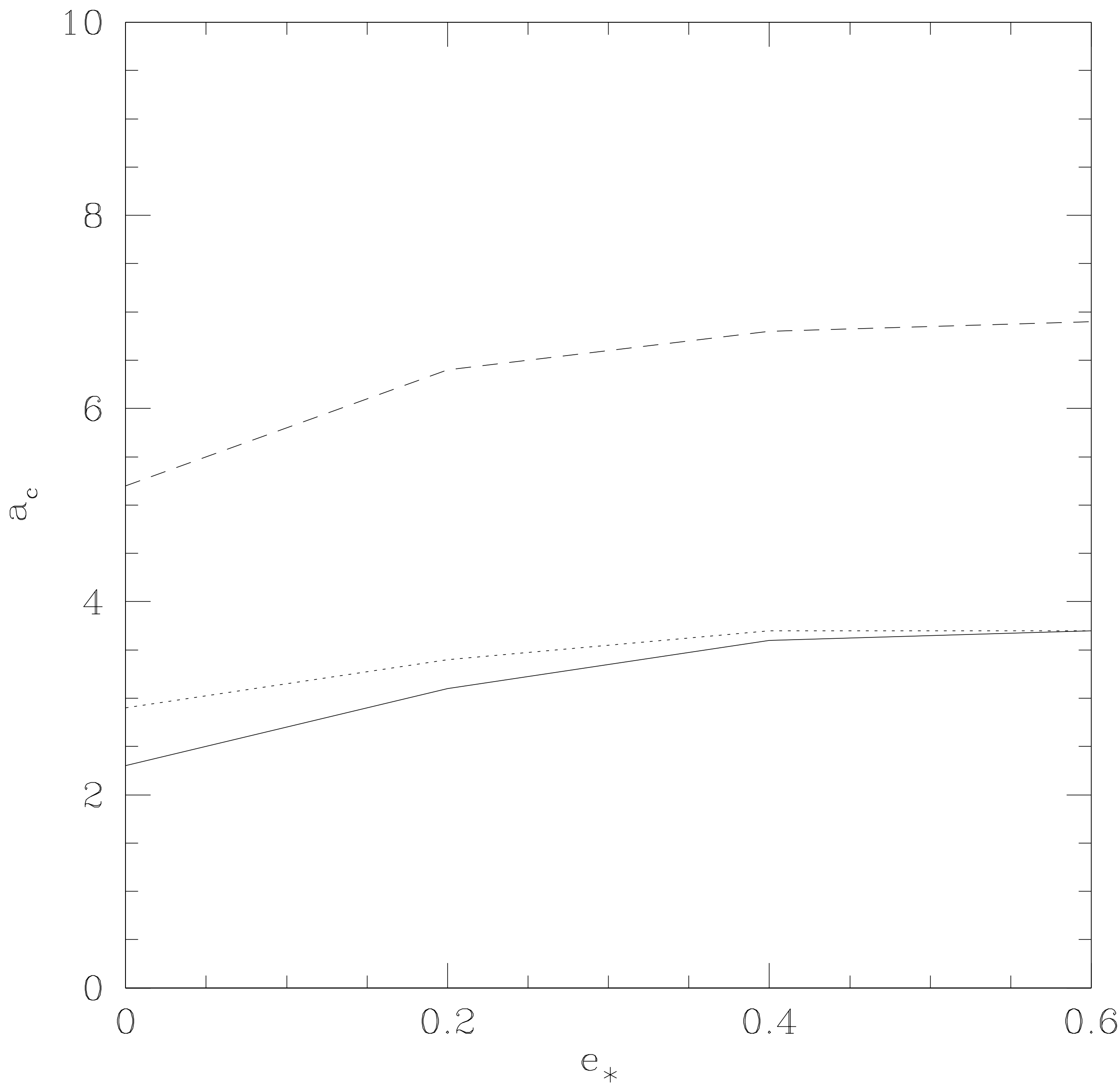

Fig. 2.— The critical semi major axis as function of eccentricity when the mass ratio of the binary system $\mu = 0.5$. The simulations were run at $e_* = 0.0$, 0.2, 0.4 and 0.6 and then the results connected by lines. The solid line represents the result for models with brown dwarfs been treated as massless test particles which initially move on circular orbits. The dotted line represents the results for models in which brown dwarfs are assigned with finite mass $\mu_b = 0.05$ and assumed to have circular orbits initially. The dash line represents the results of models in which brown dwarfs have mass $\mu_b = 0.05$ and have initial eccentricity $e_b = 0.4$.

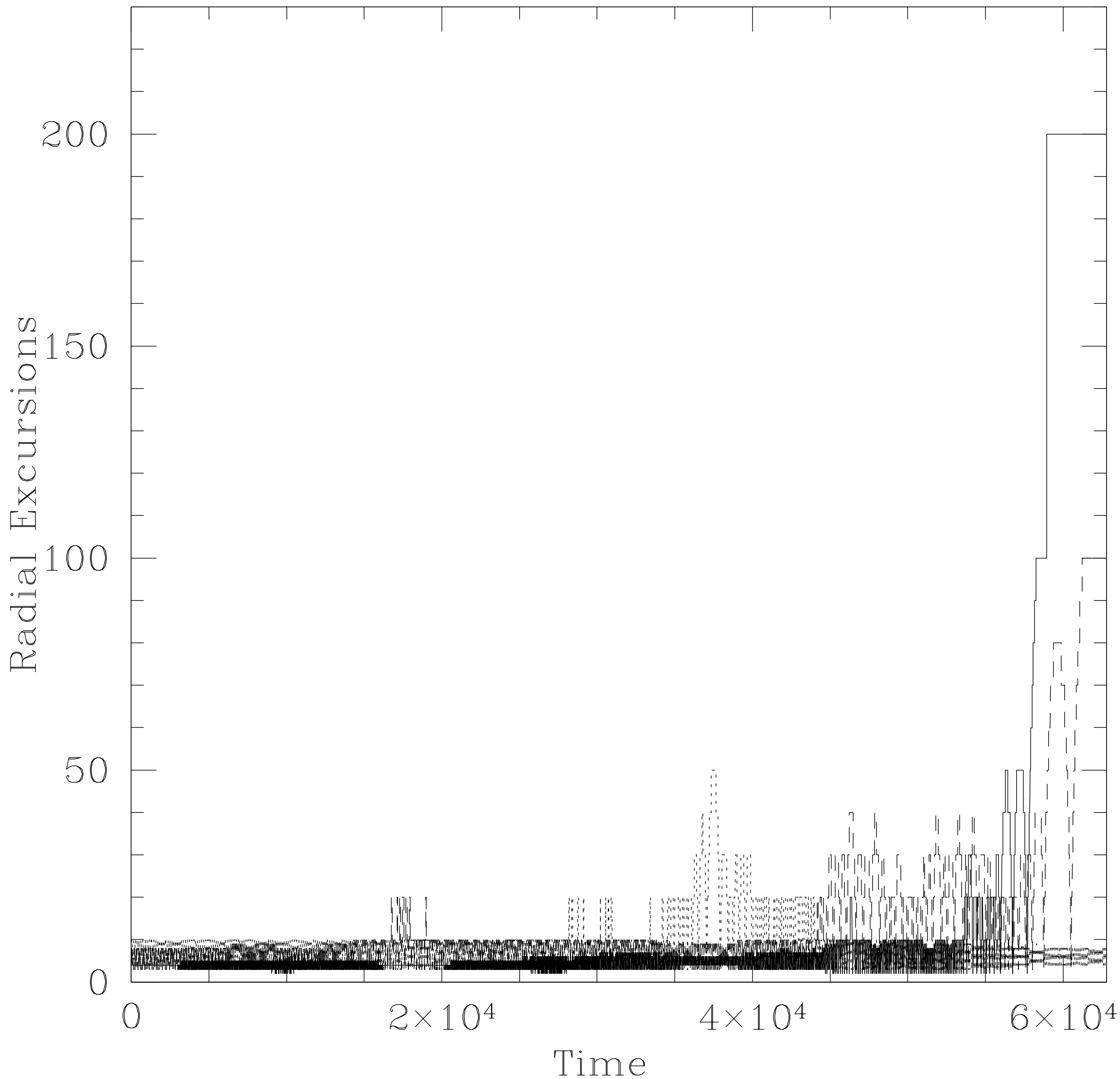

Fig. 3.— The radial excursions as function of time for model 1-3 in Section 2.2, where the solid line represents the results for model 1. The dotted and dash lines represent the results for models 2 and 3 respectively.

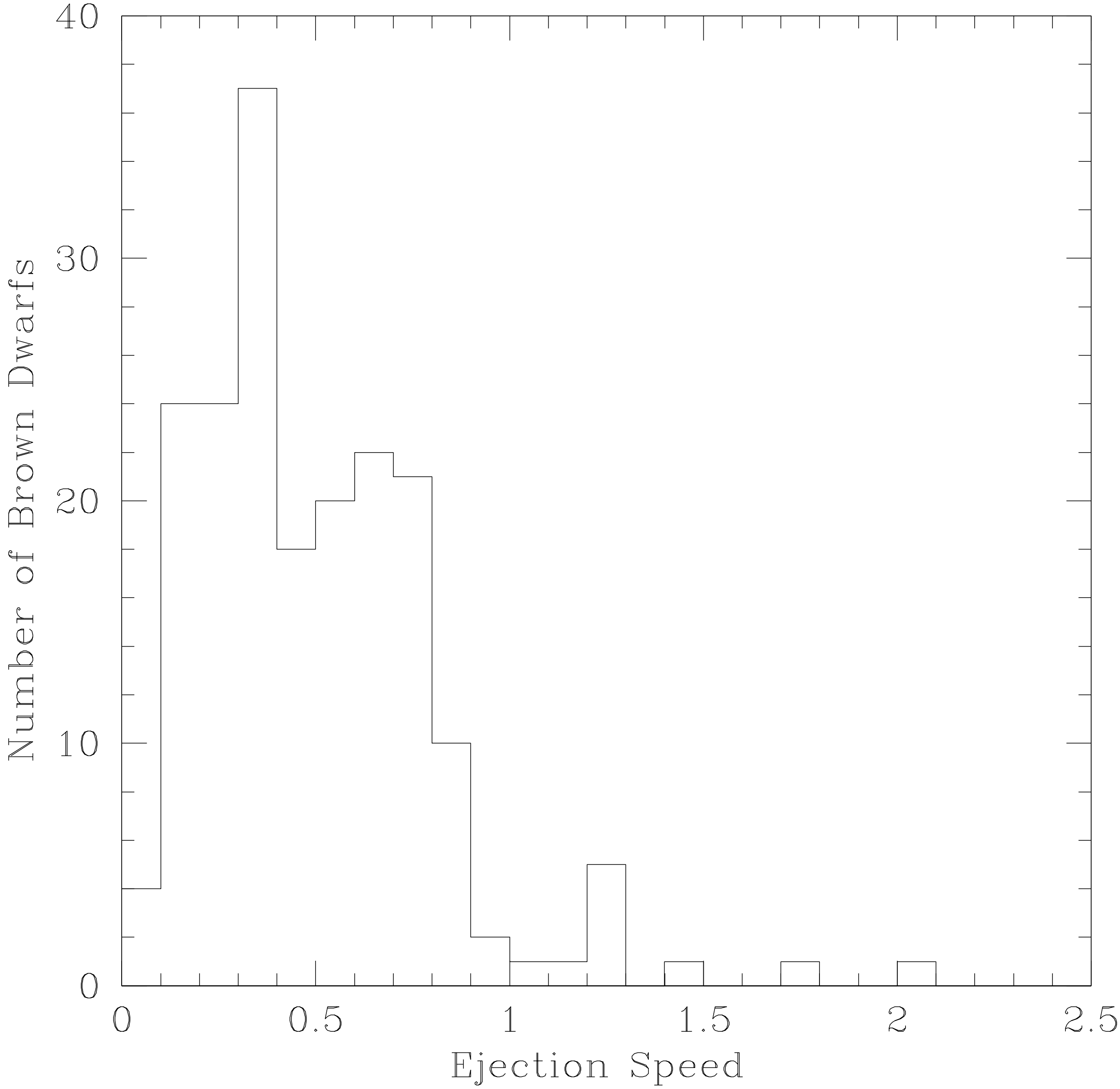

Fig. 4.— The histogram for the ejection speed of brown dwarfs, where the binary's orbital velocity is 1.